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EFFECT OF A SUDDEN CHANGE IN TERRAIN HEIGHT ON THE THREE-DIMENSIONAL LOW-LEVEL AIR FLOW, AS ESTIMATED FROM TETROON FLIGHTS[1]

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ABSTRACT

Tetroon flights across the northern California coast indicate the influence of a laterally extensive and fairly abrupt 100-m change in terrain height near the shoreline on the three-dimensional low-level air flow. Beneath the wind speed maximum at a height of 300 m, the wind speed is stronger over the land than over the sea, resulting in nearly equal horizontal mass transport between this height and the earth's surface. Across the 4-km interval bracketing the shoreline, the wind backs by 11° and 4° at heights of 200 and 400 m, respectively. The maximum upward velocity, of magnitude 6 cm sec^{-1}, occurs 250 m above the sudden change in terrain height near the shoreline, with the compensating downward motion commencing 3 km inland. Over the hills inland from the coast, the magnitude of the tetroon height variation is closely related to the magnitude of the height variations of the underlying terrain, with tetroon oscillations in the vertical generally preceding the variations in terrain height by a distance exceeding the height of the tetroon above the ground.

1. INTRODUCTION

Between mid-September and mid-October, 1964, the Pacific Gas and Electric Company, with the aid of the Air Resources Field Research Office at Idaho Falls, used an M–33 radar (owned and operated by the Meteorology Department of San Jose State College) to track more than 30 tetroon flights at Bodega Bay, 80 km northwest of San Francisco. The main purpose of the experiment was to determine air trajectories from the proposed site of a nuclear reactor. However, since many of the flights passed over Bodega Bay before moving onshore, they also serve to depict the effect on the air flow caused by a sudden change from flat to elevated hilly terrain. The effect of a change in roughness has been considered by Elliott (1958), Panofsky and Townsend (1964), and others.

2. PROCEDURES

The use of tetroons and transponders for the estimation of the three-dimensional airflow has been reported by Pack (1962). The tetroon, a superpressured constant volume balloon, tends to float along a surface of constant density, but is easily displaced from that surface by vertical air motions. Theoretical calculations (Booker and Cooper, 1965), indicate that tetroon amplitude in the vertical averages about 85 percent of air parcel amplitude for a period of vertical oscillation of 15 min, with better amplitude agreement at the shorter periods and worse at the longer periods. Moreover, because of the inertial and buoyancy forces acting on the tetroon, the vertical oscillations of tetroon and air parcel are usually slightly out of phase, a feature that will be considered in section 4.

The tetroons were released from Bodega Head, a peninsula extending southward to the west of Bodega Bay (fig. 1). The M–33 tracking radar was placed on top of a 60-m hill in the middle of this headland and in figure 1 is located at the common beginning of the tetroon trajectories. The first flights released were "skin tracked," but thereafter transponders were used to eliminate the problem of ground clutter. Tetroon positions were recorded at 1-min intervals by the tracking radar.

Table 1 gives pertinent statistics concerning the 30 flights of more than 10-min duration. The relatively short tracks in most instances are due to disappearance of the tetroons behind the hills to the east of Bodega Bay. During the time of the flights, weather conditions were typical for this area for this time of year. The North Pacific High was generally centered off the coast, and a

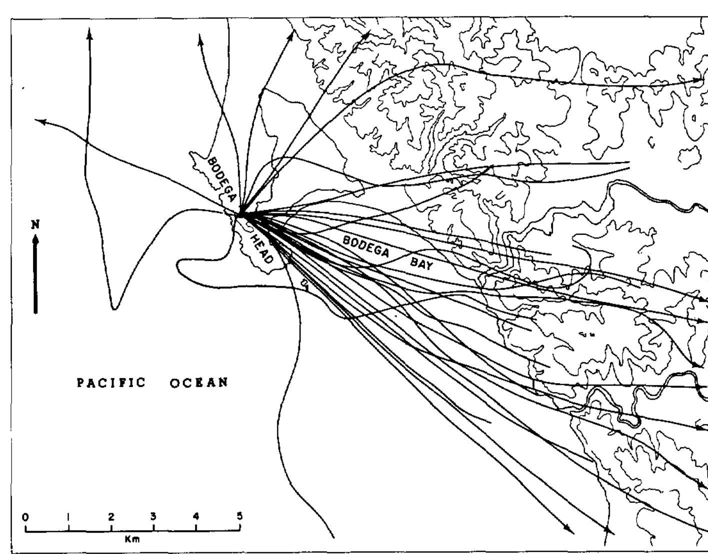

FIGURE 1.—Trajectories of tetroon flights released from Bodega Head, Calif., in September and October 1964. The arrowheads indicate that the tetroon trajectories extend beyond the boundaries of the map. Terrain height is shown at 60-m intervals. The radar was located at the common beginning of the tetroon trajectories.

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TABLE 1.—*Tetroon flights at Bodega Bay, Calif., during September and October 1964*

Flight	Launch date and time (PST)	Mean height (m)	Period of track (min)	Trajectory length (km)
1	15-1515	145	42	6.9
4	16-1556	355	24	7.2
6	17-0737	152	33	15.6
7	17-0958	186	14	8.1
9	18-0820	212	162	16.1
10	18-1222	384	38	19.4
11	22-0844	211	27	9.4
12	22-1035	110	101	11.4
13	22-1324	245	36	10.8
14	23-1000	156	72	9.6
15	23-1214	340	78	19.7
16	23-1347	279	25	9.1
17	23-1428	178	23	7.8
18	24-1206	194	31	8.0
19	24-1300	295	35	9.6
20	24-1340	94	34	7.2
21	23-1437	30	58	9.6
24	25-1455	139	31	7.3
26	26-0924	312	233	25.8
27	29-1330	367	78	20.5
28	29-1500	331	44	23.2
29	30-1410	385	21	17.7
31	1-1331	210	24	9.3
34	2-1209	204	37	6.1
36	2-1428	150	39	12.7
37	6-1412	205	42	16.8
38	7-1041	757	16	6.6
39	7-1153	591	40	18.4
40	7-1359	543	37	20.0
42	8-1110	405	42	14.5
Average	-------------------	272	52	13.0

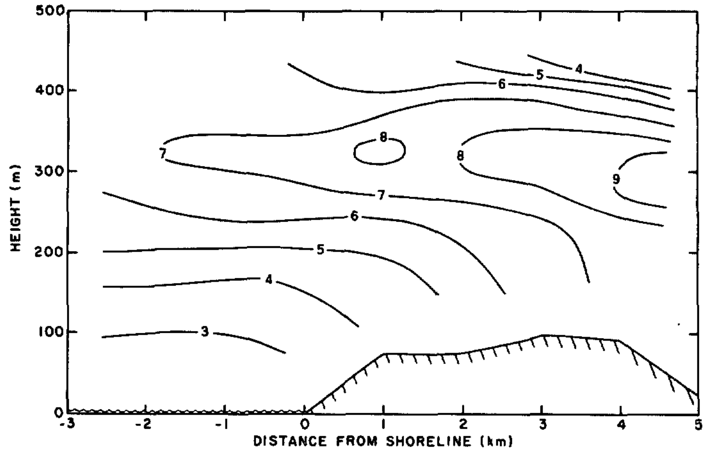

FIGURE 2.—Variation of wind speed (m sec^{-1}) with height and distance from the shoreline. In this, and subsequent diagrams of a similar nature, the tetroon data have been averaged with respect to distance from the shoreline. The mean terrain height beneath the trajectories is indicated by hatching.

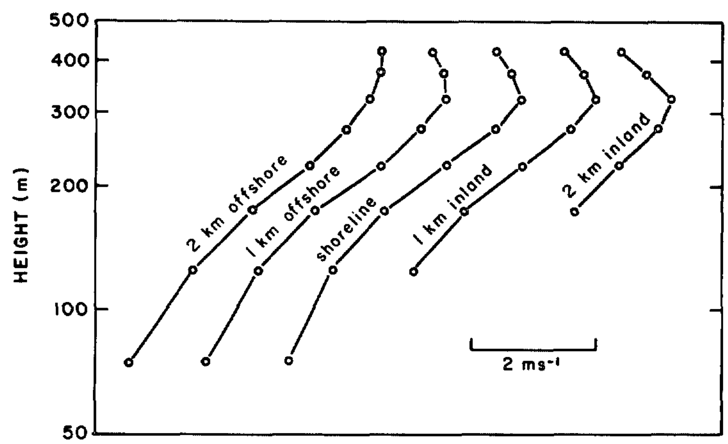

FIGURE 3.—Tetroon-derived wind speed as a function of the logarithm of height at the shoreline and at kilometer intervals from the shoreline.

trough of low pressure (heat Low) extended northward through the Central Valley of California. There were weak cold-frontal passages several times during the experiment, and the northward-directed trajectories in figure 1 usually preceded these passages. Fog and low stratus were common during the period.

3. THE FIELD OF MOTION NEAR THE SHORELINE

Figure 1 shows the trajectories or trajectory segments (arrowheads) of the tetroon flights released from Bodega Head. Fifteen of these flights, released on 6 different days, crossed the shoreline after passing over at least 5 km of water. Most of these were early afternoon flights that moved southeastward from the launch site and intersected the coast at an angle of about 45°.

Figure 2 shows the tetroon-derived wind speed as a function of height and distance from the shoreline, where for *each* of the 15 flights the shoreline was taken as the abscissa origin and the wind speed data were composited relative thereto. Of course, meteorological fields obtained by compositing data from different flights are meaningful only if steady-state conditions prevail. This requirement is generally satisfied in this area of California during the early fall. The terrain profile was obtained in a similar manner by averaging the terrain height underneath each of the 15 flights. The actual determination of the wind field in figure 2 (and in subsequent figures) involved the evaluation of the average speed over 1-km intervals from the shoreline, the apportionment of these speeds to the center of appropriate "boxes" 100 m high and 1 km wide, and the determination of an average speed at the center of "four-box" groups taking into account the number of observations in each box.

A noteworthy feature of figure 2 is the evidence for a wind speed maximum at a height near 300 m. This trend is confirmed from the average of the four vertical wind profiles obtained by means of pibals during the experiment. In the San Francisco Bay area, Miller (1968) has shown that a wind speed minimum frequently exists near the base of the inversion. The observed reduction of wind speed at heights above 300 m implies the existence of a similar wind profile at Bodega Bay. When the wind speed presented in figure 2 is plotted as a function of the logarithm of height, a nearly linear profile is obtained below 300 m, both over land and water (fig. 3). However, there

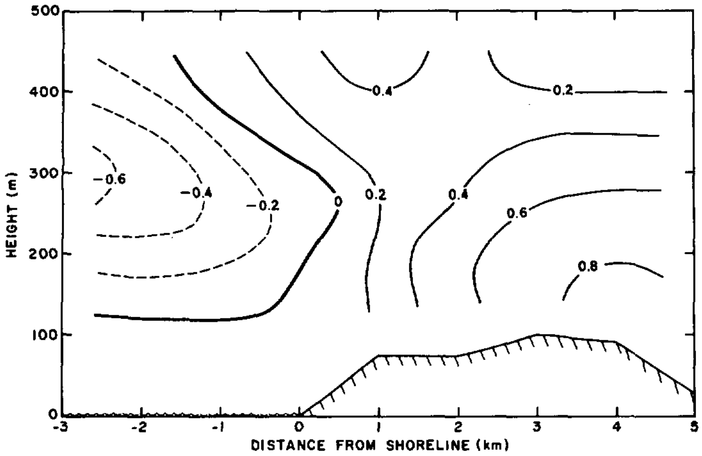

FIGURE 4.—Variation of the wind perpendicular to the "mean trajectory" (m sec⁻¹) with height and distance from the shoreline. Positive values signify flow toward the left of the mean trajectory looking downwind. Othrewise, see the legend of figure 2.

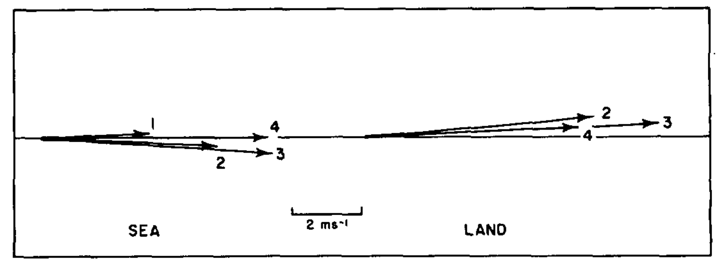

FIGURE 5.—Mean horizontal wind velocity as a function of height at points 2 km either side of the shoreline. The numbers indicate height above sea level in hundreds of meters.

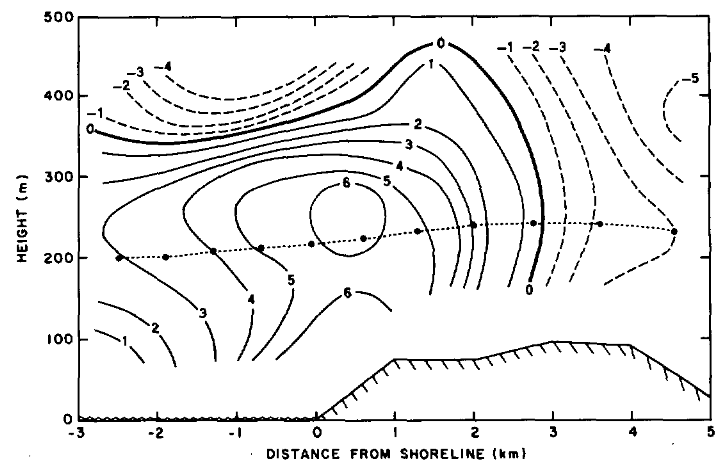

FIGURE 6.—Variation of vertical velocity (cm sec⁻¹) with height and distance from the shoreline. Positive values signify upward motion. The dotted line, with positions at 2-min intervals, represents the trajectory of an arbitrary air parcel through the mean wind field. Otherwise see the legend of figure 2.

is a tendency, particularly close to the shoreline, for the wind speed to increase with height at slightly more than the linear rate on the logarithmic diagram, suggesting that the change in terrain height near the shoreline causes a retardation of the near-surface wind *relative* to the higher level wind.

Another interesting feature of figure 2 is the increase in wind speed as the air moves inland. Over the 4-km interval that brackets the shoreline, this increase in wind speed amounts to 0.8 and 1.8 m sec^{-1} at heights of 200 and 300 m, respectively. Because of the higher wind speed above the point where the terrain height averages 80 m, there is nearly equal horizontal mass transport between the earth's surface and the height of 400 m at points 2 km either side of the shoreline. Thus, it is probable that the higher wind speed inland than at sea is due to a Venturi effect, induced by a rise in ground height and a nearly constant inversion height. The continued increase of landward wind speed in figure 2, beyond 4 km from the shore, suggests that a sea-breeze component was being added to the Venturi effect.

The turning of the air as it moves inland was determined by calculating the component of the wind perpendicular to the straight line connecting trajectory positions 5 km either side of the shoreline. Figure 4 shows, in the manner of figure 2, the average winds so obtained, where the positive values (solid lines) indicate flow toward the left looking downwind along the "mean trajectory." The resulting lateral components of the wind velocity are an order of magnitude less than the wind speeds of figure 2. The change in sense of this lateral wind occurs near the shoreline at heights of 200 to 300 m, but occurs at other heights over the sea. Note that over the land this wind is strongest near the ground; whereas over the sea, the maximum absolute value is found at a height of 300 m.

Figure 5 presents the horizontal wind velocities at 100-m height intervals at points 2 km at sea and 2 km inland, as obtained from figures 2 and 4. Over both land and sea, the wind veers with height up to 300 m. The backing in wind direction over the 4-km horizontal space interval (corresponding to about a 13-min time interval) amounts to 11°, 8°, and 4° at heights of 200, 300, and 400 m, respectively. The resulting angular velocities are comparable to the surface angular velocities noted in extratropical cyclones.

Figure 6 shows the average vertical air motion as a function of height and distance from the shoreline. The maximum upward speed, slightly exceeding 6 cm sec^{-1}, is located 250 m above the abrupt change in terrain slope just inland from the shoreline. This location is slightly in error (too close to the shoreline) due to the phase difference between tetroon and air parcel discussed in section 4. The sinking motion more than 3 km inland would be anticipated from the decrease in mean terrain height and may also be associated with the upward motion near the coast through the Brunt-Vaisala wavelength. The dotted line in figure 6 represents the trajectory of

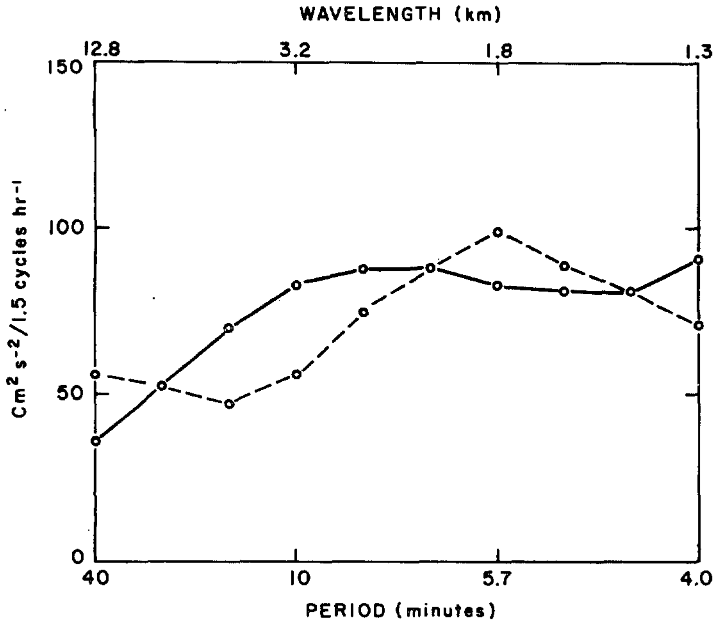

FIGURE 7.—Composite vertical velocity spectra obtained from the eight longest tetroon flights over the land (solid line) and from hypothetical balloons following along the earth's surface beneath the tetroon trajectories (dashed line). The wavelength in kilometers appropriate to the mean tetroon speed is indicated at the top.

an arbitrary air parcel, initially at a height of 200 m, that passes through the mean fields of wind speed (fig. 2) and vertical motion (fig. 6). The change in air parcel height is seen to be about half the change in terrain height.

The strong downward motion just offshore at a height of 400 m in figure 6 is based on only two flights, and perhaps is not completely representative. Such a sinking motion may indicate the existence, in a highly modified form, of a sea-breeze circulation regime.

4. THE VERTICAL AIR FLOW OVER THE HILLS

The solid line in figure 7 represents the composite vertical velocity spectrum for the eight tetroon flights tracked for the longest period of time over the hills to the east of the shoreline. A very weak spectral peak occurs at a period of vertical oscillation of 7.5 min, which, with the given mean wind speed of 5 m sec^{-1}, corresponds to a mean Lagrangian wavelength of about 2.5 km. For comparison, the dashed line shows the composite vertical velocity spectrum for hypothetical balloons following along the earth's surface directly below the tetroons and moving with the speed of the tetroons. The dominant wavelength of the terrain determined thereby is about 1.8 km. Thus, there is evidence that even in the composite average the tetroons are not oscillating in the vertical exactly in response to the terrain, presumably because the atmospheric stability, expressed through the Brunt-Vaisala period, is not sufficiently strong.

TABLE 2.—*Correlation and quadrature correlation (correlation for a 90° phase lag) between tetroon oscillations in the vertical and variations in terrain height beneath the tetroon, for periods of oscillation between 10 and 5 min. A positive quadrature correlation signifies that the tetroon fluctuation in the vertical occurs upwind from the fluctuation in terrain height*

Flight	*Correlation*	*Quadrature correlation*
13	0.12	0.88
15	.01	.05
24	.74	−.11
26	−.82	.58
27	.61	.42
28	−.43	.30
37	.27	.47
42	−.17	.49
Algebraic average	.07	.38
Absolute average	.39	.41

It is of interest to compare the height variations of tetroons and underlying terrain. In order to avoid contamination of the data by periodicities of little interest to us, we have restricted the analysis to periodicities between 10 and 5 min (recall the 7.5-min tetroon period above). Over this period interval, and taking each flight as an entity, the average correlation between root-mean-square (rms) tetroon vertical velocity and the rms vertical velocity of the hypothetical balloon following along the earth's surface beneath the tetroon is 0.80. Accordingly, at heights a few hundred meters above the surface the vertical air motion is strongly influenced by topography, as would be expected.

The cross spectrum between tetroon vertical velocity and the vertical velocity of the hypothetical balloon following along the earth's surface beneath the tetroon yields phase-lag information. Again confining the analysis to periods of oscillation between 10 and 5 min, table 2 presents the correlation and quadrature correlation for the individual flights as well as the average absolute and algebraic values for all eight flights. Here the correlation is defined, for each flight, as the ratio of cospectrum between tetroon and terrain to the average of the spectra of the tetroon and terrain, while the quadrature correlation is defined as the ratio of the quadrature spectrum between tetroon and terrain to the average of the two spectra. In seven out of eight cases, the quadrature correlation is positive, indicating a systematic tendency for the tetroon vertical fluctuations to be displaced upwind from the fluctuations in terrain height. The tendency for an in-phase relation is less convincing, with positive correlations occurring in only five out of eight cases.

The angular phase difference between tetroon vertical fluctuations and terrain-height fluctuation was determined from the ratio of quadrature spectrum and cospectrum for the period interval 10 to 5 min and is shown plotted (dots) as a function of mean tetroon height in figure 8. The scatter is very large, with the fluctuation in tetroon height preceding (occurring upwind of) the fluctuation in terrain height by as much as 145° and following it by as much as 8°. On the average, the tetroon oscillation pre-

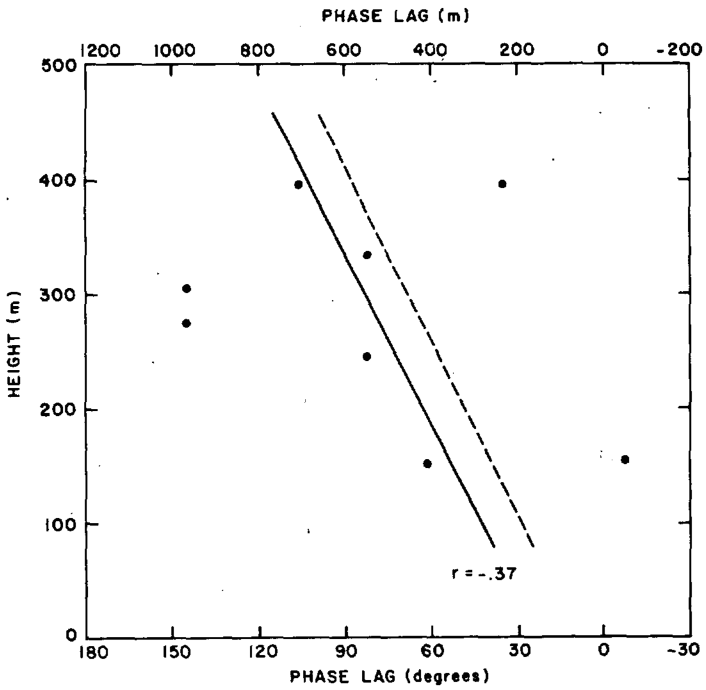

FIGURE 8.—For the period interval 5 to 10 min, the phase lag between tetroon vertical oscillations and terrain-height fluctuations for the eight flights (dots), and the derived regression line as a function of tetroon height (solid line). A positive phase lag signifies that upward tetroon movement precedes increase in terrain height. The dashed regression line shows the correction for the phase difference between vertical oscillation of tetroon and air parcel. The phase lag in meters, derived from the mean tetroon speed, is indicated at the top.

cedes the terrain oscillation by 81°. At the top of figure 8, the phase differences have been expressed in meters based on an average of the 2.5- and 1.8-km dominant wavelengths for the vertical fluctuations of tetroons and terrain.

Although figure 8 exhibits a tendency for the phase difference between terrain and tetroon oscillation to be greater at the greater tetroon heights (solid regression line), the correlation of -0.37 is not significant. The uncertainty in the data is indicated by the fact that this regression line does not pass through zero lag at mean sea level, let alone at the earth's surface which averages 90 m in height under these flights. Part of this discrepancy is due to the inertial and buoyancy forces acting on the tetroon, which results in the vertical tetroon trajectory being displaced upwind of the air parcel traejctory. Thus, the phase difference between air parcel and terrain is not as large as the phase difference between tetroon and terrain. Theoretical calculations utilizing the appropriate drag coefficient for the tetroon indicate that, for a period of oscillation of 6 min and amplitude of 100 m (close to the individual values for the eight tetroon flights), the phase difference between air parcel and tetroon is 20 sec, which corresponds to a distance of 100 m for the given mean tetroon speed of 5 m sec^{-1}. The dashed regression line in figure 8 shows the phase lag between air parcel and terrain derived in this manner. Zero phase lag is still not indicated at the earth's surface. It is apparent that eight tetroon trajectories are simply not sufficient to yield a realistic estimate of the variation with height of the phase lag between air parcel and terrain.

5. CONCLUDING REMARKS

While the above results must be considered preliminary, the tetroon appears a useful tool for probing the atmosphere in regions and at heights not easily accessible to Eulerian-type measurements. Comparable data could, at the present time, only be obtained from aircraft flights. In this particular tetroon analysis, uncertainty is introduced by the necessity of compositing data obtained on different days. This is probably a reasonable procedure in the California coastal regions, but it certainly would not be reasonable in most regions. Thus, customarily one would be faced with having to make many tetroon flights during a single day, with all the difficulties inherent in the tracking of many tetroons with one or two radars. The tracking of numerous balloons would be feasible if tetroon height could be obtained separately, so that only tetroon positions in the horizontal (PPI scope) had to be obtained by radar. It appears more and more obvious that the full potential of the tetroon system can only be realized when our dependence on tracking radars is relaxed through the development of a suitable aneroid capsule for height determination.

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